HIGH ENERGY MISSILE PROJECT

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ABSTRACT

In the search for increasing the lethality and survivability of light armoured vehicles, a small hypervelocity missile concept has been investigated. This research and development project called High Energy Missile (HEMi) technology demonstrator aimed at studying and demonstrating the key technologies to achieve the appropriate lethality to defeat modern main battle tanks at long range in a lightweight missile. The HEMi concept is described and a review of the supporting technologies is made with emphasis on the technical challenges.

1. INTRODUCTION

In 1999, a Defence R&D Canada-Valcartier (DRDC Valcartier) study carried out for the Armoured Combat Vehicle (ACV) project concluded that a 105-mm tank gun did not have sufficient growth potential to destroy a modern main battle tank (MBT) for all possible kill mechanisms. Furthermore, a strap-on kinetic energy (KE) missile was concluded to be the best option for a light armoured vehicle (LAV) to effectively engage and destroy a modern MBT. Other Operational Research (OR) studies have also found TOW Under Armour (TUA) vehicles very vulnerable on the battlefield due to the TOW 2B's long time of flight and subsequent prolonged exposure of the firing platform. Moreover, chemical energy rounds/missiles can be defeated by Explosive Reactive Armour, which has forced complicated and costly tandem warhead and top attack missiles to be developed.

The results of these studies and the fact that the Canadian Forces are progressively making LAVs the mainstay of their land-armoured fleet led to the proposal in 2000 and approval in 2001 of the Technology Demonstration Program HEMi. The main objectives of HEMi are: to clarify the firepower requirements and technological options available for a new fleet of light fighting vehicles; to demonstrate the key technologies essential to a small hypervelocity missile system applicable to LAV weapon systems and capable of defeating a modern MBT at ranges between 400 m and 5 km; to provide the Canadian Forces with the technological insight to support smart acquisition of anti-armour weapon systems for light combat vehicles; to demonstrate an alternate, lighter technological concept to gun systems applicable to LAV weapon systems; and to reduce the time to field the Army's next generation direct fire anti-armour capability.

The project is lead by scientists from DRDC Valcartier and is carried out with industrial participants and the support of Canadian Land Forces. HEMi involves multiple technological domains including: propulsion, lethality, aerodynamics, structure, guidance & control and modeling & simulation. The project is carried out through paper studies, technology prioritization, system level trade-off and integration studies, identification of alternatives, operational research studies and development of prototype missile components and a hardware-in-the-loop facility (HIL). Project deliveries comprise various missile components and software developed in support of the studies to verify the most critical aspects of the technology and mitigate the risk. In terms of hardware, both missile sub-systems and individual components demonstrators are built. A booster casing (with surrogate material), a dart containing a segmented rod, a dual-purpose control actuation mechanism, a guidance link hardware and an integrated nozzle and thrust vector mechanism are the main missile system demonstrators. Individual component demonstrators such as a separation mechanism, a dart control module for the HIL and a terminal effect demonstrator (supported by extensive modeling & simulation studies of segmented rod effects on heavily-armoured vehicles) will also be delivered.

2. HEMI CONCEPT

The fundamental HEMi concept is a 23-kg, 1.2-m hypervelocity missile based on an advanced kinetic energy penetrator (e.g. long rod, segmented or telescopic penetrators), accelerated to the hypervelocity regime within a 400-meter range by a

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high-performance solid rocket motor, and flying at this regime to at least a 5-km range. More specifically, the current HEMi design (Fig. 1) uses a two-stage missile approach for energy conservation purposes. It involves a booster and a dart both being guided. After ignition, the booster accelerates the missile to 400 m reaching a speed of approximately 2400 m/s and then the dart is ejected from the booster. After separation the dart coasts to target maintaining the lethality specification up to 5 km.

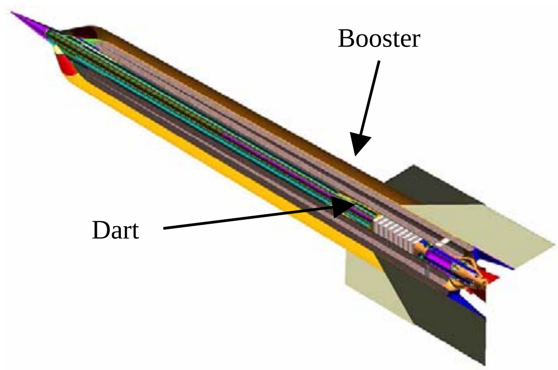

Figure 1. HEMi concept.

The HEMi missile flight is divided in three phases: the boost phase, the separation phase and the guided dart flight.

The boost phase lasts for the first 0.4 s and 400m of flight. During this period, the rocket motor accelerates the missile to Mach 7 while the controls and guidance bring the missile near the launcher to target line-of-sight.

At 400m, the missile has reached its velocity and is on line-of-sight. A target engagement at this reach would have the greatest chance of success. However, if a target is at shorter range, the missile may miss the target because launch transients are not totally cancelled by guidance. Even if the missile hits the target, lower missile velocity may provide insufficient kinetic energy to penetrate the target armour.

When the missile reaches 400m, the missile is stabilized near the line-of-sight and the motor ends burning. A short unguided separation phase begins. The dart slides out of the booster on a range of about 100-200 m. No guidance is possible during this phase because any lateral control force would hurt the separation. For this reason, during this phase, the missile accuracy slightly decreases.

During the dart guidance phase, the missile glides to target. A predictive integrated guidance law is used to achieve beam-rider guidance. Unlike traditional beam-rider guidance that continuously keeps the missile on the line-of-sight beam between the launcher and the target, the proposed guidance method guides the missile on a trajectory that intersects the beam at a specific range corresponding to the expected target range. To improve lethality of the long-rod warhead, a constraint on the angle-of-attack of the missile at the target is used. Given the actual missile states, a model is used to predict the future missile states at the target. A control command is computed so that the missile is on the beam with a null angle-of-attack at the target. The dart drag causes the missile to decelerate progressively.

2.1 Lethality

The penetrator should have the capability of penetrating 1000 mm of equivalent rolled homogeneous armour (RHA). This latter requirement coupled with the other criteria suggested that it was difficult to use current long rod penetrators to satisfy the penetration requirement and therefore, there was a need to investigate novel penetrators. An extensive analysis using numerical simulations has been conducted to address this lethality issue. Different types of novel projectiles were investigated and a segmented rod projectile (Fig. 2) was selected as a candidate penetrator that could satisfy HEMi's lethality requirement. The penetration mechanics of segmented rod projectiles with different segment length to diameter (l_s/d_s) ratios striking semi-infinite RHA target was examined using numerical simulations. The impact velocity was 2200 m/s. The penetration results obtained were compared to that of the parent monolithic rod. The results showed that an extended segmented rod projectile could penetrate a semi-infinite target more than 60 percent deeper than a continuous rod projectile of the same material and with a length equal to the sum of the lengths of the individual segments of the segmented rod. It was shown that increased penetration is obtained as the segment l_s/d_s ratio is decreased. The results showed that a segmented rod with a mass of 2.6 kg and segment l_s/d_s suitably optimized produced approximately the same depth of penetration as a 4.1-kg continuous rod striking the target at the same impact velocity of 2200 m/s. Given that these results were obtained from numerical studies, experimental verification of the chosen rod and segment parameters forms the first experimental program of DRDC Valcartier newly built hypervelocity impact studies (HVIS) facility. The HVIS facility consists of a two-stage light gas gun launcher with a 120-mm pump tube and a 50-mm launch tube. The launcher is equipped with a modern velocity measuring system at the muzzle and an x-ray system to examine the projectile attitude before and after the sabot trap and before the impact on the target. This aspect is quite important when launching delicate packages such as a segmented rod projectile.

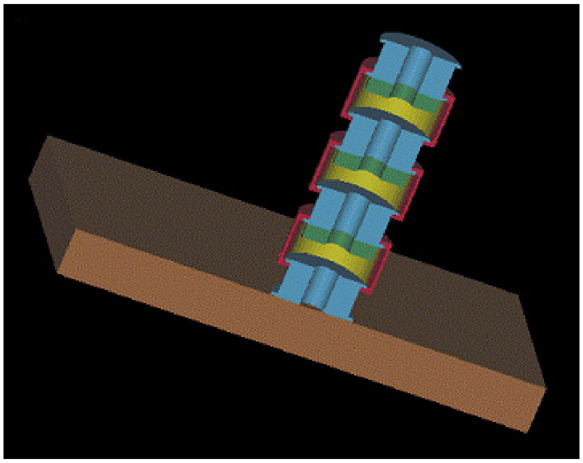

Figure 2. Segmented rod projectile penetration.

Selecting a segmented rod projectile for HEMi does pose some risks given that even though this projectile has been studied from a penetration standpoint at various laboratories through out the world a prototype has not as yet been tested. This issue of launching and deploying a segmented rod is one of the most difficult problems that needed to be addressed to satisfy the lethality requirement of HEMi. DRDC Valcartier has addressed this issue and examined and developed robust engineering methods to launch and deploy a segmented rod projectile within a missile system. Moreover, a prototype of segmented rod will be fired using the gas gun facility in October 2004. The dart will be compressed at launch and the deployment will take place during the guided dart flight phase. This will be followed by a series of subsequent firings that will allow to confirm the model predictions and optimize the rod design.

2.2 Propulsion

In order to rapidly accelerate the penetrator to the hypervelocity regime within a 400m range, the high performance solid rocket motor (SRM) booster must contain a high energy, high loading density, fast-burning propellant in order to maximize the delivered energy and minimize the burn time. One approach to achieve a potential increase in specific impulse (I_{sp}) and decrease the time for energy delivery is to operate the SRM at a very high pressure. A substantial gain (up to 15%) is obtainable from existing propellant formulations. In addition, this also results in a tangible increase in the burn rate. Analysis showed that an operating pressure in the 35-70 MPa (5000-10000-psi) range, depending on the existing propellant chosen, is needed to obtain the necessary mass flow rates. This is about 3 to 5 times the operating pressure of existing in-service propulsion systems. Parametric studies on the other hand, showed that for the casing material considered for the booster motor, an operating pressure of 20 MPa (2900 psi) was optimal and that no further gain could be realized by operating at higher pressure. The current HEMi design value of I_{sp} is 2440 N-s/Kg (249 s), and is representative of what can realistically be achieved with minimum-smoke propellant formulations and a non-ideal nozzle.

Choices in the design of the HEMi motor were being guided by the need, to optimize and/or minimize inert component mass, to carry sufficient propellant, to optimize the conversion of chemical energy into impulse and to precisely control the flight trajectory of the missile.

Inert component mass is comprised of items such as the motor casing, insulation and struts along with the nozzle and thrust vector control jet vanes. Optimization of inert component mass involves primarily the motor casing and is achieved by operating the motor at the pressure defined by the point where the effect of increasing I_{sp} is countered by the effect of increasing mass. Minimization of inert component mass is obtained by the judicious choice of component materials (high strength-to - weight ratio) and by the choice of a propellant grain configuration that minimizes the amount of required casing insulation and the variation in pressure throughout motor burn. The rod-and-tube grain configuration was chosen to deal with both these issues (Fig. 3). From the perspective of minimizing required insulation a cylindrical tube is much more favourable than the conical tube used in the present design. However, the present grain design has been constrained by the external aerodynamics. Inert casing weight can also be minimized by the choice of a grain design that results in a maximum chamber pressure that is as similar as possible to that of the average chamber pressure. The smaller the difference between these two values, the more a motor burn is said to be neutral.

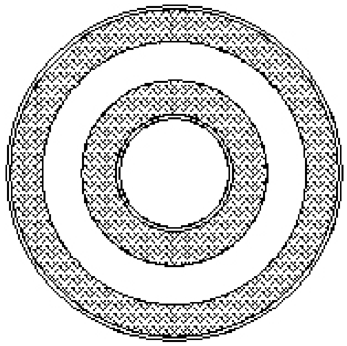

Figure 3. Rod-and-tube grain design

Varying the nozzle throat area can also regulate the average chamber pressure. This is especially important for propellant formulations with high burning rate exponents and high temperature sensitivities. In the present design, one option is to implement passive variation of the nozzle throat area through differential strain capacities of the motor casing and the inner tube supporting the pintle. Propellant mass is a function of the propellant density, the grain configuration and the internal volume available within the casing. The conical shape of the present casing design limits available volume compared to that of the cylindrical shape.

The motor nozzle is the primary component for conversion of chemical energy into impulse. As such, maximum possible expansion ratio and nozzle profiling must be considered. From the perspective of expansion ratio, it is possible that a nozzle exit diameter greater than the actual motor diameter may be an optimal configuration. The concept of energy conversion also involves minimizing thrust losses. As such, the thrust vector control system must be such that axial thrust loss is minimized. Although jet vane thrust vector control is not ideal from this perspective, assuming that a material can be found which will sustain minimal erosion and allow the vanes to be as thin as possible, axial thrust losses should be acceptable.

Precise control of the missile flight trajectory is both a hardware and software issue. From the perspective of the hardware, it is essential that the component giving control authority maintains its function throughout the flight. For the jet vane this translates into minimum erosion. However, it is also important that no other components create unexpected and uncontrollable actuation forces. For the present configuration, the pintle nozzle shape is critical in this regard. At the time of motor assembly, it is essential that the pintle be accurately centred within the nozzle expansion cone. In addition, it is important that unwanted pintle movement and throat erosion be controlled throughout the burn. The former issue can be addressed by proper component and subsystem design. The later issue will depend on finding high strength low erosion materials.

2.3 Aerodynamics

As mentioned earlier, the HEMi flight is based on three phases: booster, separation, and dart flight. An aerodynamic design was done for each of these phases.

A baseline geometry for the booster was established, based on geometry, mass and stability constraints, in order to compare the impact of changes. The shape selected has a double-angle conical nose, a body with a slight conical shape to increase stability and four fins. Such a shape made possible to meet the expected dimensions of the missile and should be capable of carrying the dart. The model prediction showed that the missile is more stable in the subsonic region and, as it accelerates, it stability margin diminishes. More stability margin in the subsonic region is good as the dynamic pressure to generate aerodynamic forces and moments is small. Also, there was a fin span constraint as the missile must fit in a launch tube. Several shapes were considered in the investigations. The best solution must have good aerodynamic properties, in addition to a simple folding mechanism and an overall mass of the fins that is as small as possible. The most promising fin set was found to consist of four wrap-around fins of clipped delta shape.

The booster and dart designs considered that a separation occurs and that this separation is a sliding separation as the dart will overcome the booster. Various approaches were investigated through modeling and validation in wind tunnel experiments to gather aerodynamics characteristics during the separation phase. Presently, the retained solution is a passive separation relying on booster drag. Further experiments are being done based on firing subscale prototypes with a gun to get a better understanding of separation aerodynamics at high speeds.

Two main families of dart concepts were identified: darts with front control and darts with rear control. In order to better grasp the impact of the various dart dimensions for both families, a parametric study dealing with the main dimensions was undertaken. The objective was to compare the retard, the lateral acceleration and the stability of each configuration. The study was supported by wind tunnel experiments with subscale prototypes (Fig. 4).

The dart with rear control provides some significant advantages over the dart with front control. This is assuming that a dart with rear control can be designed to be stable without fins. The advantages are the elimination of the fins, with their negative effect on mass, deployment and ablation, a smaller retard, and the possibility to combine the control section of the dart with the control section of the booster. The disadvantages of the rear configuration are the fact that a window for the guidance cannot be located at the front, which would make acquisition of the guidance signal easier during the booster phase when the dart is embedded in the booster. Another potential disadvantage is the fact that canards cannot be used for control. In view of this evaluation of the pros and cons, the HEMi team favoured the rear configuration, which was further examined.

Figure 4. Wind tunnel experiments on the dart.

There were several aerodynamic control methods that could potentially be used to control the dart. Because of the high speed and aeroheating, the conventional methods of lifting surfaces are unlikely to be successful. Methods that have a good potential include bending noses, flaps, base flow alteration, and reaction jet control. The performance of the flap control, which was seen as the simplest method to simulate, was estimated with a simple approach. A flap located at the rear or the control section would be well located with respect to the actuators. Modeling permitted to establish the best flap configuration and dimensions to meet the HEMi missile requirement (Fig. 5).

2.4 Guidance

There are three phases in the guidance sequence but they all rely on one set of guidance sensors located into the dart. The first phase occurs in the boost phase and relies on a laser beam rider (LBR) command line of sight type of guidance where the laser source feeds an encoded pulsed laser signal into the missile sensors. The laser is also used to track the missile in flight. With such a missile tracker, the laser beam may follow the missile trajectory in the booster phase and maintain a relatively narrow laser beam onto the missile. This has the advantage to increase the signal-to-noise ratio at the sensor while the beam is propagated through the perturbation of the motor plume. In the boost phase, since the dart is still inserted into the booster, the laser beam energy is routed to the detectors by optical fibre links. The wavelength of operation has been selected based on a compromise between a good penetration of smoke and atmospheric aerosol, miniaturization potential of detector technology and support electronics, laser source maturity and beam conditioning and encoding capability.

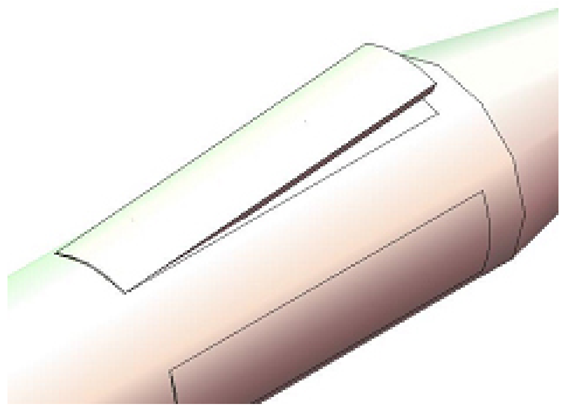

Figure 5. Control flaps of the HEMi dart.

The second phase of guidance is an unguided one, which occurs during the dart ejection from the booster where the guidance sensors are momentarily blind. This phase will be very short to insure stable missile trajectory.

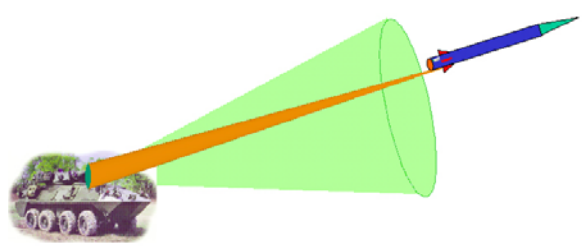

Figure 6. Laser beam rider guidance

The third phase occurs when the dart is in free flight following the separation. In that case, the guidance technique is the same as in the boost phase except that the detectors are now directly exposed to the incoming laser radiation.

A predictive guidance law that minimizes the control authority necessary to achieve the specified precision governs the whole guidance process. This translates to minimum weight and volume of the control actuators and batteries. This guidance method, unlike the traditional beam-rider guidance that continuously keeps the missile on the line-of-sight beam between the launcher and the target, guides the missile on a trajectory that is near the beam with a null angle-of-attack at a specific range corresponding to the expected target range.

2.5 Control

The flight control of the booster and dart is respectively achieved by jet vanes and aerodynamic flaps. The entire system is packaged into the dart aft end. One set of electronics powered by thermal lithium batteries handles all guidance, navigation and control functions including missile uplink. Because of this and the short flight time of the missile, the processing function requires maximum throughput capability and minimal system latencies. The flight control is based on an electromechanical system featuring small DC brushless motors providing independent control mechanisms (Fig. 7). This system controls both the booster’s jet vanes and the dart’s aerodynamic flaps. The same set of electric motors is used for the booster and the dart and it is expected that these motors will be driven to their physical thermal limits at missile impact.

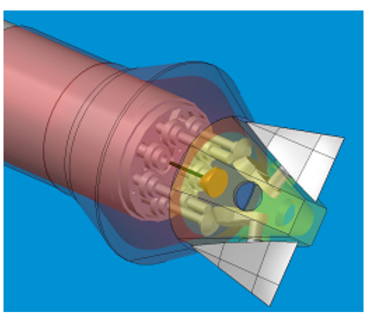

Figure 7. Flight control packaging in the dart.

Upon receiving a launch command, the thermal batteries will be initiated and brought up to operating voltage. Electronics will be powered up as well as any necessary inertial devices and their status bit checked. When this check is communicated as successful, the firing pulse will be allowed to enter and initiate the rocket motor. Jet vanes will be commanded to zero at launch and then commanded free at some time after the missile exits the launch tube or clears the rail. Following release, the electronics will lock up on the laser signals and begin decoding uplink data. Four channels provide complete pitch, yaw and roll control. After separation, a course correction of the dart is initiated through use of the rear aerodynamic flaps.

2.6 Structure

An over-wrapped metallic pressure vessel has been selected for the booster case. A parametric study examining nine different materials was undertaken. The materials ranged from metals such as steel and titanium, to metal-matrix composites such as aluminium-lithium, graphite-magnesium and silicon carbide-aluminium, to polymer matrix composites such as graphite-epoxy. A graphite-epoxy dart tube concept has been selected. To prevent buckling of the tube wall and to provide support to the dart, eleven sabot-like carriers will be spaced equally along the length of the dart. The total weight of the dart tube with sabots is 415 g.

The heat load on the dart and the booster due to high-speed flow were estimated using engineering methods and Computational Fluid Dynamics (CFD). The analysis included various material properties and geometries and served in material and configuration selection.

Investigations are continuing on the development of an expansion mechanism for the dart. Major issues to resolve include conversion of potential energy in internal or external sources into kinetic energy to expand the dart, mechanism packaging and mechanical design that controls the bending modes and frequencies of the compressed and expanded dart.

2.7 Modelling and simulation

Since it is not planned to develop, build and fly the overall missile during the present phase of the project, a large part of the studies rely on modelling and simulation (M&S). M&S has been used in the detailed component designs, the system concept definition and the system design & analyses. Engineering-level (physics-based) simulation tools (including DATCOM, hydrocodes and combustion CFD) were used for the design and optimization of the components of the hypervelocity missile, including the airframe flight aerodynamics, propulsion system, kinetic energy penetrator design and its terminal effects, and laser based guidance.

The component models are integrated into a virtual representation of the hypervelocity missile concept that is integrated into a HIL facility (Fig. 8) including hardware guidance and control components developed to demonstrate a virtual flight of the missile. Engineering models are verified and validated using information derived from the hardware development and testing of the missile components.

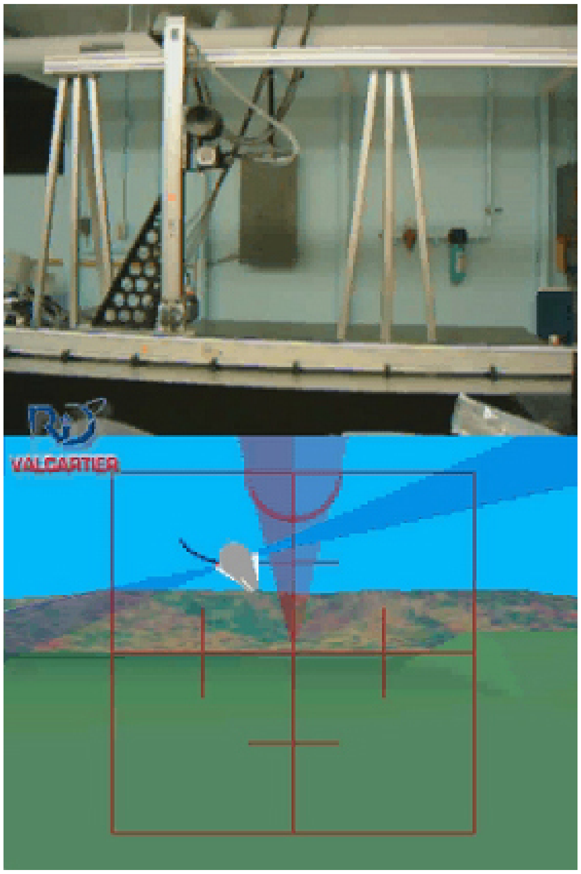

Figure 8. Hardware-in-the-loop facility

3. POTENTIAL BATTLEFIELD IMPACT

An operational research study has been carried out to quantify the effects of replacing 105-mm armour piercing fin stabilized discarding sabot (APFSDS) rounds with the HEMi in a typical battlefield scenario. The study has shown that the HEMi has the potential to be an excellent replacement for the APFSDS in that it can increase the total number of kills and the ranges at which these kills occur. However, more studies with higher fidelity modelling will be necessary to further investigate the problem and end up with more solid conclusions.

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CONCLUSION

In summary, the concept developed under the HEMi project has the potential to provide the appropriate lethality against advanced armour protection systems including ERA. Also, due to its fast time of flight, the HEMi will minimize the exposure time of the firing platform, which is critical for the survival of a light combat vehicle. The short time of flight and small cross sectional area will make the HEMi difficult to detect and counter by Defensive Aids Suites (DAS). The increased range of the HEMi (5 km) over the current 105 mm APFSDS round (2.4 km) will allow early attrition of the enemy outside the range of their direct fire weapons, again increasing survivability. Its small size will increase the number of stowed rounds, reduce the overall vehicle weight and the logistics burden. The knowledge and understanding derived from the HEMi TD will help develop and/or support the acquisition of a future direct fire weapon system that will give the Canadian Forces a capability across the full spectrum of conflict. Ultimately, if the HEMi TD determines that a hypervelocity KE missile can be accurately delivered from a lightweight moving platform and destroy a tank at a range of 5 km or longer, the Canadian Forces could conceivably end up using a single light combat vehicle. Such a vehicle, offering the lethality and survivability of a heavy MBT, would bring about the revolution in doctrine and tactics that the Canadian Forces are seeking for their next generation of combat vehicles.
Finally, the HEMi growth potential includes achieving longer ranges, use from other platforms such as helicopters or the 'Plug and Play' missile launcher turret presently studied by the US Army that would allow a force to be easily and quickly tailored by selecting the appropriate weapon system(s) for the mission.